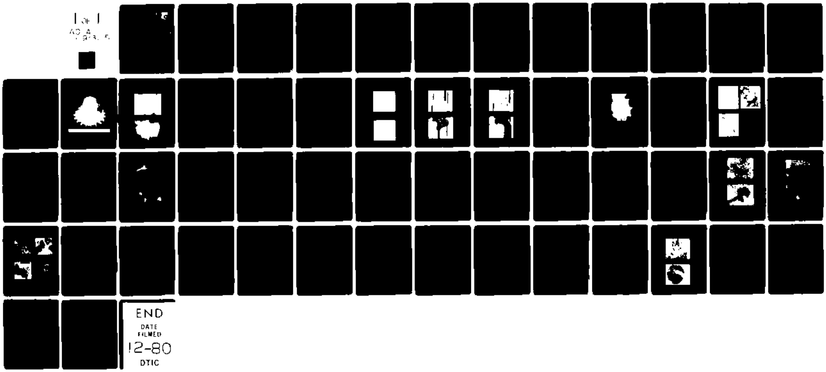
AD-A091 305 AIRESEARCH MFG CO OF ARIZONA PHOENIX F/G 11/6
HOT ISOSTATIC PRESSING/HEAT TREATMENT OF CAST SUPERALLOY AF2-1D--ETC(U)
JUN 80 J R KIDWELL, D V SUNDBERG, M FUJII F33615-75-C-2016
UNCLASSIFIED 31-3292 AFWAL-TR-80-4076 NL



AFWAL-TR-80-4076

LEVEL

HOT ISOSTATIC PRESSING/HEAT TREATMENT OF CAST SUPERALLOY, AF2-1DA, RADIAL TURBINE WHEELS

JAMES R. KIDWELL
DAVID V. SUNDBERG
MUNEO FUJII

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
402 S. 36 STREET
PHOENIX, ARIZONA 85010

FEBRUARY 1980

TECHNICAL REPORT AFWAL-TR-804076
FINAL REPORT FOR PERIOD 6 MAY 1975 - 15 JULY 1979

APPROVED FOR PUBLIC RELEASE;
DISTRIBUTION UNLIMITED

MATERIALS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio 45433

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

Kenneth L. Kojola

KENNETH L. KOJOLA
Project Engineer

FOR THE COMMANDER

H. A. Johnson

H. A. JOHNSON
Chief, Metals Branch
Manufacturing Technology Division

"If your address has changed, if you wish to be removed from our mailing list, or if the addressee is no longer employed by your organization please notify AFWAL/MLTM, W-PAFB, OH 45433 to help us maintain a current mailing list".

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

19 REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: 18 AFWAL-TR-80-4076

2. GOVT ACCESSION NO.: AD-A091305

3. RECIPIENT'S CATALOG NUMBER:

4. TITLE (and Subtitle): 16 Hot Isostatic Pressing/Heat Treatment of Cast Superalloy AF2-1DA, Radial Turbine Wheels.

5. TYPE OF REPORT & PERIOD COVERED: 9 Final Report, 6 May [redacted]975-15 Jul 79

6. PERFORMING ORG. REPORT NUMBER: 14 31-3292

7. AUTHOR(s): 10 James R. Kidwell, David V. Sundberg, Muneo Fujii

8. CONTRACT OR GRANT NUMBER(s): 15 F33615-75-C-2016

9. PERFORMING ORGANIZATION NAME AND ADDRESS:
AiResearch Manufacturing Co. of Arizona
A Division of The Garrett Corporation
Phoenix, Arizona 85010

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS:

11. CONTROLLING OFFICE NAME AND ADDRESS:
Air Force Materials Laboratory
Air Force Systems Command
Wright-Patterson AFB, Ohio 45433

12. REPORT DATE: 11 Jun[redacted]80

13. NUMBER OF PAGES: 45

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): 12 56

15. SECURITY CLASS. (of this report): Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approval for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Forty AF2-1DA alloy radial turbine wheels were cast and X-ray inspected. Thirty-eight wheels were free of obvious defects and selected for evaluation. As-cast elevated temperature tensile strength was measured and as-cast/heat threated tensile and stress-rupture properties were determined. Eight wheels were HIPped in four combinations with temperatures varying from 2150 to 2250°F, pressures of 15 or 29 ksi, and a constant three-hour time period.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

404796

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

Four solution heat treatment temperatures were selected based on a previous investigation to cast a modified AF2-1DA alloy composition (AFML Contract Number F33615-71-C-1573). Evaluations were performed using four HIP conditions and eight HIP/heat treatment combinations of four wheels each. Samples were examined metallographically and tensile and stress-rupture properties were determined. Four HIP/heat treatment combinations were selected for LCF testing on the basis of acceptable microstructures and mechanical properties. Room temperature strain-control LCF tests were performed and results analyzed on a Weibull distribution. Data analysis indicated that LCF life improvement was obtained through HIP and heat treatment. Specifically, a 3X LCF life improvement was achieved for as-cast wheels predicted to fail in less than 1000 cycles.

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

FOREWORD

This report was prepared by AiResearch Manufacturing Company of Arizona, A Division of The Garrett Corporation, Phoenix, Arizona for a separate effort under Contract F33615-75-C-2016. This contract was sponsored by the Aero Propulsion Laboratory and was entitled "Advanced Technology Components for Model GTP305-2 Aircraft Auxiliary Power System." The Metals Branch of the Manufacturing Technology Division, Materials Laboratory provided funding to the APL contract for a separate effort to improve the low cycle fatigue properties of the Model GTP305-2 APU radial turbine wheel. Mr. K. L. Kojola (AFWAL/MLTM) was the Project Engineer, and Mr. J. R. Kidwell was the Project Engineer for AiResearch for the effort which is documented in this report. Mr. D. V. Sundberg and Mr. M. Fujii were the principal investigators and major contributors to the program.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

LIST OF TABLES

SUMMARY

Forty AF2-1DA alloy radial turbine wheels were cast and X-ray inspected. Thirty-eight wheels were free of obvious defects and selected for evaluation. As-cast elevated temperature tensile strength was measured and as-cast/heat treated tensile and stress-rupture properties were determined. Eight wheels were HIPped in four combinations with temperatures varying from 2150 to 2250°F, pressures of 15 or 29 ksi, and a constant three-hour time period. Four solution heat treatment temperatures were selected based on a previous investigation to cast a modified AF2-1DA alloy composition (AFML Contract Number F33615-71-C-1573). Evaluations were performed using four HIP conditions and eight HIP/heat treatment combinations of four wheels each. Samples were examined metallographically and tensile and stress-rupture properties were determined. Four HIP/heat treatment combinations were selected for LCF testing on the basis of acceptable microstructures and mechanical properties. Room temperature strain-control LCF tests were performed and results analyzed on a Weibull distribution. Data analysis indicated that LCF life improvement was obtained through HIP and heat treatment. Specifically, a 3X LCF life improvement was achieved for as-cast wheels predicted to fail in less than 1000 cycles.

SECTION I

INTRODUCTION

The original AiResearch Model GTP305-1 Auxiliary Power Unit (APU) radial turbine rotor design, required a forging of AF2-1DA alloy. A cast AF2-1DA alloy rotor was designed and tooled as a means of cost reduction for the AiResearch Model GTP305-2 APU. Casting and heat treatment processes were developed under the Materials Laboratory (AFWAL/ML) engine demonstration program.

Air Force Model GTP305-2 APU applications require specific low-cycle-fatigue (LCF) life of the rotating components to satisfy projected service-life requirements. However, cast AF2-1DA alloy radial turbine wheels were projected to have marginal LCF properties in the as-cast and heat treated condition. Therefore, hot isostatic pressing (HIP) was proposed to improve fatigue life by closing casting microshrinkage and eliminating crack initiation sites (Air Force Contract F33615-75-C-2016, General Electric Company). Demonstration of this phenomenom was previously accomplished during Air Force and AiResearch programs on cast INCO 713LC radial turbine wheel, used in a commercial APU, that is currently in production.

A program was proposed to AFWAL/ML to investigate HIP and subsequent heat treatment, as a means of improving the Model GTP305-2 APU radial turbine wheel LCF life. This effort was funded as an add-on to an existing Propulsion Laboratory contract for unit design and rig testing (Contract Number F33615-75-C-2016). The AFWAL/ML program consisted of two tasks:

- Task I - Characterization of Baseline Material

- Task II - Application and Evaluation of HIP and Revised Heat Treatment

Under Task I, the determination of mechanical properties and microstructures of the baseline Model GTP305-2 cast AF2-1DA radial turbine wheel was accomplished. Previously developed baseline heat treatment was used on these turbine wheel castings. Room temperature LCF baseline material properties and elevated temperature tensile and stress-rupture strengths were determined using test bars removed from cast turbine wheel hub sections.

In Task II, evaluation of HIP/heat treat process combinations was performed to assess AF2-1DA LCF property response. Four different HIP cycles and four heat treatments were used in eight combinations. Material property data screening (room temperature tensile and elevated temperature stress-rupture) was conducted to select four final candidate HIP/heat treat combinations for room temperature strain controlled LCF evaluation.

The ultimate objective was to establish a manufacturing process for HIP and subsequent heat treatment utilizing Air Force manufacturing technology funding.

SECTION II

TECHNICAL DISCUSSION

2.1 Task I - Characterization of Baseline Material

The AF2-1DA alloy radial turbine wheel castings evaluated were procured from AiResearch Casting Company (ACC), Torrance, CA. A typical Model GTP305-2 radial turbine wheel casting is shown in Figure 1. Wheel serial numbers, master heat numbers (from Cannon-Muskegon Corp.) and cast AF2-1DA alloy chemistry are presented in Table 1.

Forty cast AF2-1DA turbine wheels were X-ray inspected for hub defects. Thirty-eight were defect free while two showed possible inclusions near the center (S/N 62 and S/N 94). These two castings were not used for evaluation.

One wheel (S/N 40) was sectioned to examine the internal and surface grain structure Figure 2. Internal and external grain structures were compared with previous Model GTP305-2 castings and were comparable. Elevated temperature tensile tests were performed on the material from wheel S/N 40, to determine material strengths at typical HIP temperatures. Results of the four bars (0.179 inch diameter by 1.0 inch gauge), tested at 2200°F, are presented in Table 2. Average measured ultimate strength was 4500 psi and measured elongations varied from 4.3 to 18.5 percent. No explanation was evident for the ductility spread based on location of the test specimens or the grain size of the etched test bar gauge sections. The ductility spread is considered to be due to a coarse grain that behaved as a properly oriented single crystal.

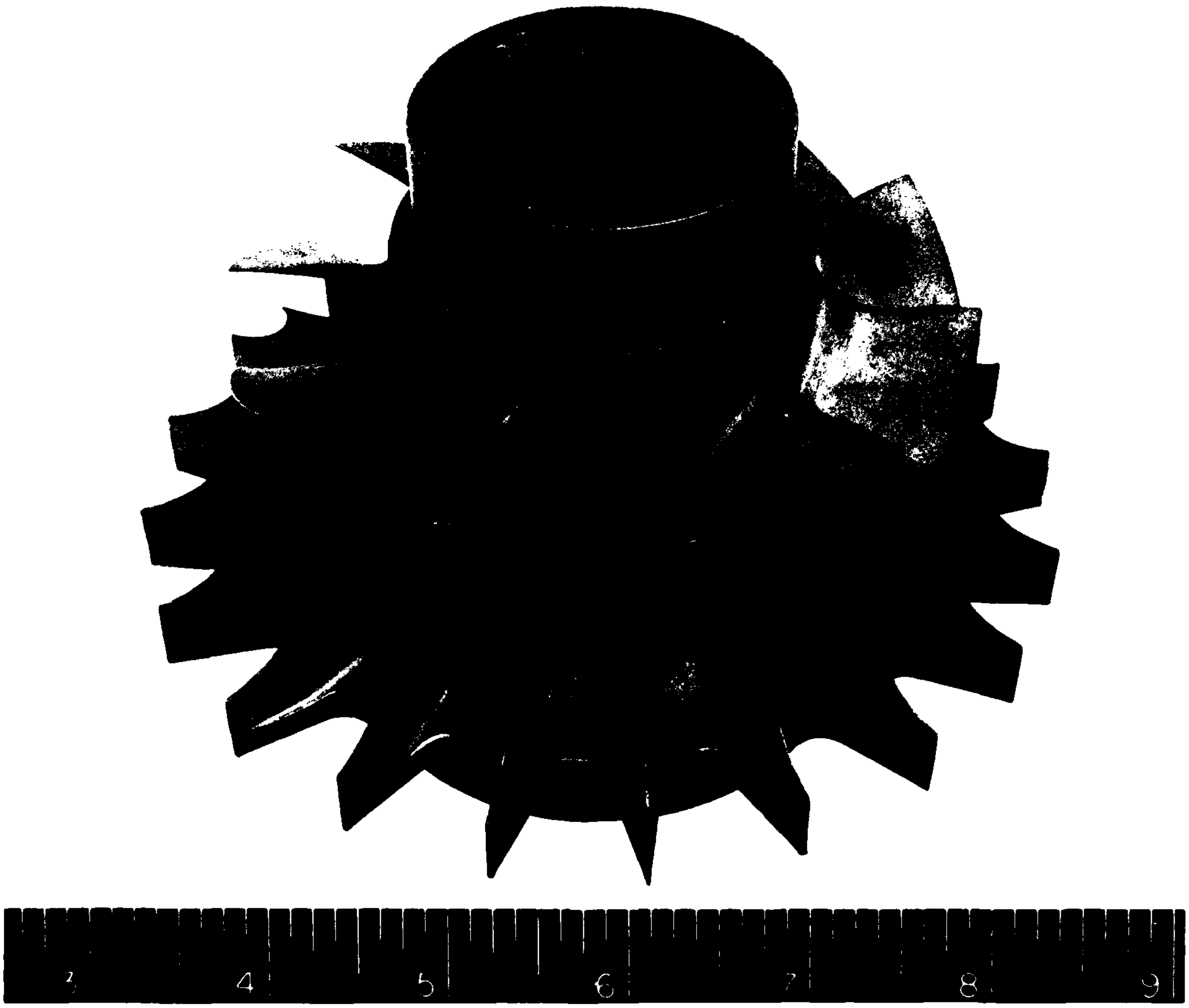
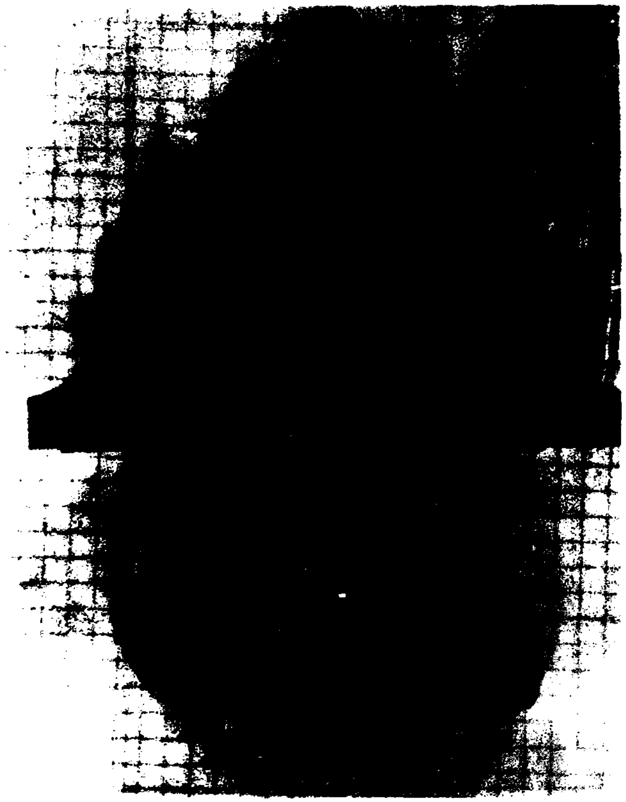
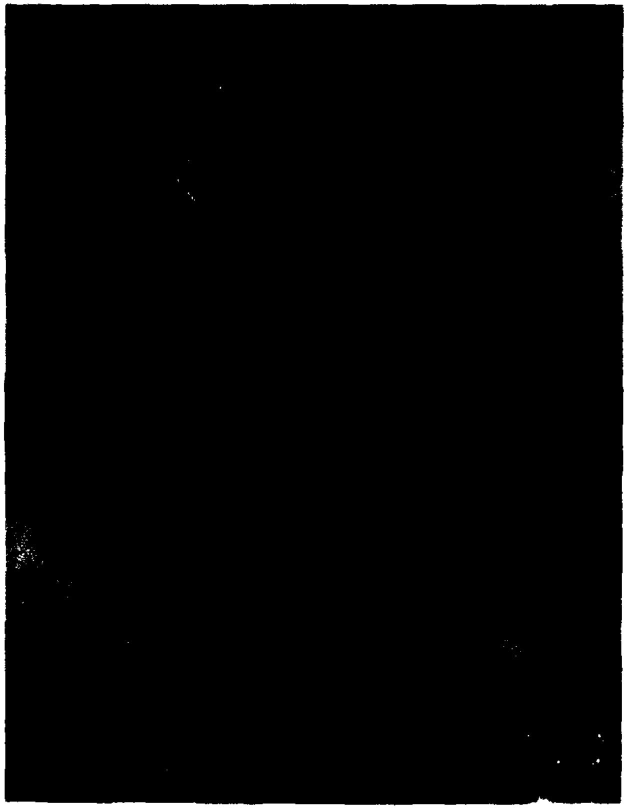


Figure 1. Cast AF2-1DA alloy GTP305-2 radial turbine wheel



EXTERNAL SURFACE
ETCH: $HCL-H_2O_2$



INTERNAL GRAIN STRUCTURE
ETCH: $HCL-H_2O_2$

Figure 2. Macroscopic grain structure produced in cast AF2-1DA alloy radial turbine rotor

TABLE 1. SERIAL NUMBER, MASTER HEAT NUMBER AND CAST AF2-1DA ALLOY CHEMISTRY

Wheel S/N	Master Heat No.	Wheel S/N	Master Heat No.	Wheel S/N	Master Heat No.
40	VF43	60	VE947	81	VE955
41		61		82	
45		63		83	
48		64		88	
51		66		89	
62		67		90	
68		69		91	
73		70		92	
79		71		93	
80		72		94	
85		74		95	
86		75		96	
87		76			
		77			
		78			

Element	Specification Chemistry Range Weight Percent	Cannon-Muskegon Corp. Master Heat No. Chemistry VF43	VE947	VE955
Carbon	0.12-0.16	0.13	0.13	0.12
Cobalt	9.5-10.5	9.8	9.8	9.8
Chromium	11.0-12.0	11.7	11.7	11.4
Molybdenum	2.7-3.3	3.1	3.0	3.0
Tantalum	1.4-2.0	2.0	2.0	1.92
Titanium	2.5-2.9	2.9	2.8	2.8
Aluminum	4.4-4.8	4.7	4.7	4.7
Tungsten	4.5-5.5	4.8	4.9	4.7
Hafnium	0.9-1.3	1.2	1.1	1.1
Boron	0.010-0.018	0.011	0.014	0.016
Zirconium	0.03-0.07	0.038	0.035	0.037
Iron	0.25 max	<0.20	<0.20	<0.20
Silicon	0.25 max	<0.20	<0.20	<0.20
Manganese	0.25 max	<0.20	<0.20	<0.15
Sulfur	0.015 max	<0.01	<0.01	<0.01
Phosphorus	0.015 max	<0.01	<0.01	<0.01
Nickel	Bal	Bal	Bal	Bal

TABLE 2. 2200°F TENSILE PROPERTIES OF AS-CAST AF2-1DA ALLOY MEASURED ON TESTS BARS MACHINED FROM A TURBINE WHEEL

Specimen Number	0.2% YS (psi)	UTS (psi)	EL (%)	RA (%)
40-3	3400	4400	4.3	7.8
40-7	2800	4000	6.9	12.7
40-5	3600	4600	18.0	24.6
40-8	3500	4900	18.5	29.5

YS = Yield Strength
UTS = Ultimate Tensile Strength
EL = Elongation
RA = Reduction of Area

2.1.1 Heat Treated AF2-1DA

Five cast wheels (S/Ns 72, 75, 81, 83, and 87) were selected to establish the heat-treated (un-HIPped) baseline properties. Heat treatment cycles, as developed in the basic GTP305-2 APU program were as follows:

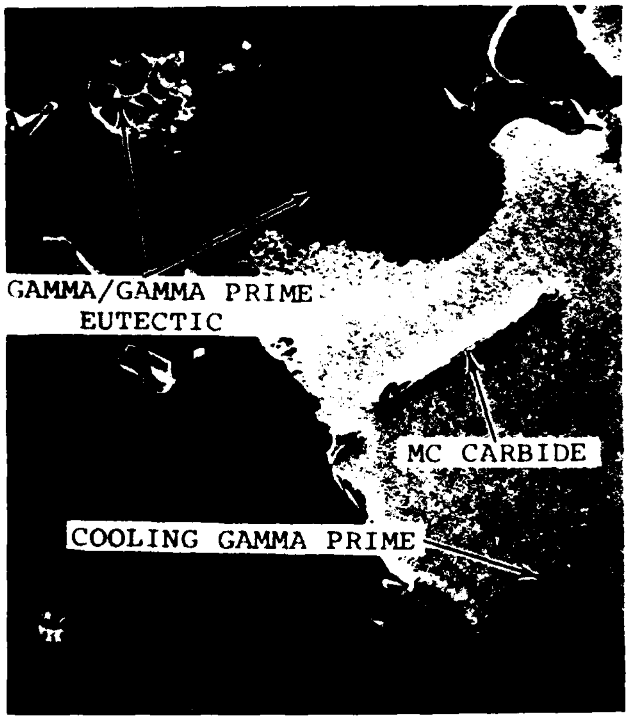
- o Solution: 2175 $^{+20}_{-0}$°F/2 hours/gas cool
- o Intermediate Age: 1950 ±25°F/2 hours/gas cool
- o Age: 1400 ±25°F/16 hours/air cool

Solution treatments were performed in a vacuum furnace capable of heat treating up to sixteen wheels and obtaining a designated cooling rate of 45 to 50°F per minute (observed by gas cooling) from the solution and intermediate age temperatures. Cooling rates from the 2175°F solution, and 1950°F intermediate age temperature, were determined using a thermocouple inserted in the hub section of a scrap turbine wheel casting. This procedure provided an accurate measurement of the hub section cooling rate. After heat treatment, the five castings were fluorescent penetrant inspected with no evidence of surface cracks.

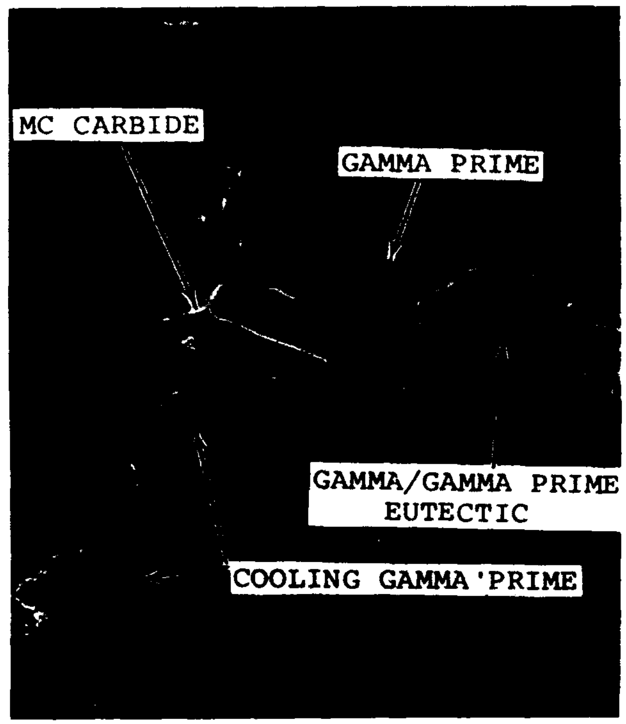
Scanning Electron Microscope (SEM) evaluation of the as-cast and heat-treated baseline material was performed. Figures 3 and 4 show SEM micrographs at 100 and 500X magnifications, respectively. The as-cast microstructure exhibits typical primary MC carbides, gamma/gamma prime eutectic cooling gamma prime and the absence of grain boundary precipitates. Microstructural changes observed after heat treatment, were the appearance of grain boundry precipitates and a reduction of gamma prime size, as shown in Figure 5. Small amounts of undissolved cooling gamma prime are also evident.

AS CAST (100X) HEAT TREATED (100X)

Figure 3. SEM micrographs of as-cast and heat-treated microstructure of the hub region of the GTP305-2 turbine casting

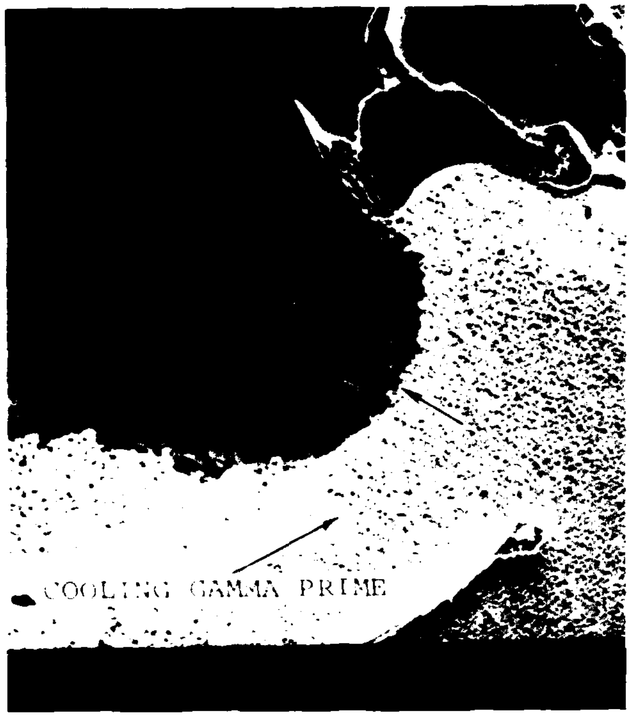


AS CAST (500X)



HEAT TREATED (500X)

Figure 4. SEM micrographs of as-cast and heat-treated microstructure of the hub region of the GTP305-2 turbine casting



AS CAST (1000X)

HEAT TREATED (1000X)

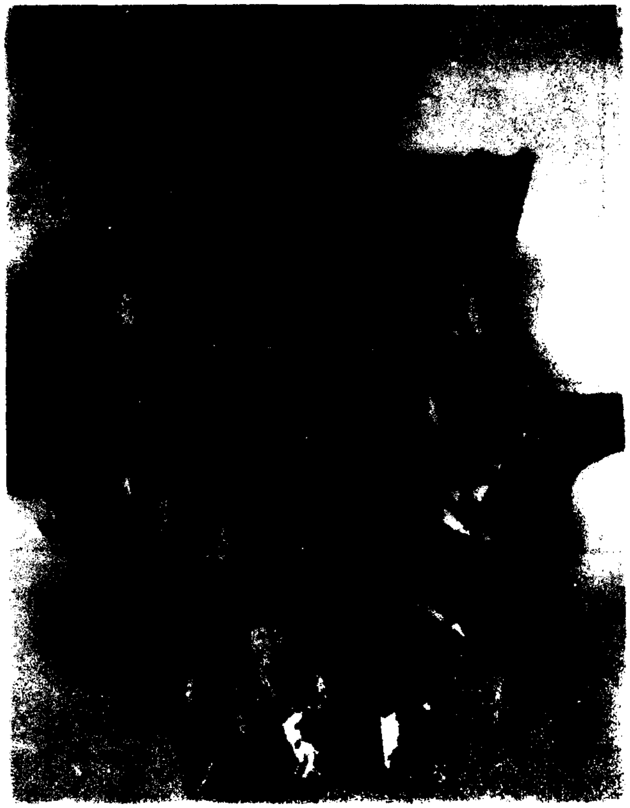
Figure 5. SEM micrographs of as-cast and heat-treated microstructure showing grain boundary areas (arrows)

2.1.2 Mechanical Property Determinations

Location of mechanical property test specimens removed from the castings is shown in Figure 6. Tensile and stress-rupture testing were performed at Joliet Metallurgical Laboratories, Inc., Joliet, Illinois, and low-cycle-fatigue (LCF) testing at Mar-Test Inc., Cincinnati, Ohio.

Results of tensile tests performed on 0.250-inch diameter by 1.0-inch gauge test bars at room temperature and 1400°F, are presented in Table 3. Room-temperature ultimate strength of specimen number 75-3 and room-temperature elongation measurements on all specimens were slightly below specification minimums. Tensile properties obtained at 1400°F were above specification minimums. Examination of room-temperature tensile test bar fracture surfaces was performed using a Scanning Electron Microscope (SEM) in an attempt to explain elongation measurements of less than 5 percent. SEM examination of fracture surfaces revealed evidence of microporosity on all room-temperature tensile test bars (Specimens No. 72-3, 75-3, and 83-5). The degree of microporosity observed appeared to be typical for as-cast superalloy turbine wheels. SEM micrographs of the microporosity observed on the test bar fracture surfaces are shown in Figure 7. No evidence of any anomaly was found to explain elongation measurements of less than 5-percent.

Stress-rupture testing was performed using 0.250-inch diameter by 1.0-inch gauge test bars at 1400, 1600, and 1800°F, utilizing stresses that were selected to give an average rupture life of 100 hours. Results are presented in Table 4. As shown, rupture times and ductilities were above specification minimums when rupture times versus stresses are plotted on a Larson-Miller parameter basis (see Figure 8).



1 and 2, LOW-CYCLE-FATIGUE
4 and 6, CREEP-RUPTURE
3 and 5, TENSILE
7 and 8, TENSILE (AS-CAST CONDITION)

LOCATION OF TEST SPECIMENS FOR MECHANICAL PROPERTY TESTING

Figure 6. Location of test specimens for mechanical property testing

TABLE 3. ROOM AND ELEVATED TEMPERATURE TENSILE PROPERTIES OF HEAT-TREATED* (UN-HIPped) CAST AF2-1DA ALLOY TURBINE WHEELS

Specimen Number	Temperature (°F)	0.2% YS (ksi)	UTS (ksi)	EL (%)	RA (%)
72-3	RT	122.4	133.6	3.6	13.7
75-3	RT	120.1	125.7	4.3	10.5
83-5	RT	129.0	144.7	4.8	8.0
72-5	1400	111.7	134.5	5.7	14.3
81-3	1400	112.1	142.5	5.9	13.5
87-3	1400	114.0	134.3	6.3	16.4
Property Specification Minimums**	RT 1400	115.0 105.0	130.0 130.0	5.0 5.0	

*2175°F for 2 hours with Argon Quench; plus 1950°F for 2 hours with Argon Quench; plus 1400°F for 16 hours with air cooling.

YS = Yield Strength
UTS = Ultimate Tensile Strength
EL = Elongation
RA = Reduction of Area

**Developed under AFML Contract F3365-75-C-2016

SPEC. NO. 72-3

SPEC. NO. 75-3

SPEC. NO. 83-5

Figure 7.

SEM MICROGRAPHS (500X) SHOWING MICROPORSITY (ARROWS) ON FRACTURE SURFACES OF ROOM TEMPERATURE TENSILE TESTED BARS FROM BASELINE AS-CAST AND HEAT-TREATED GTP305-2 TURBINE WHEEL CASTINGS.

TABLE 4. ELEVATED TEMPERATURE STRESS RUPTURE PROPERTIES OF HEAT-TREATED* (UN-HIPped) CAST AF2-1DA ALLOY TURBINE WHEELS

Specimen Number	Temperature (°F)	Stress (ksi)	Hours to Rupture	EL (%)	RA (%)
72-6	1400	90	152.4	4.0	10.6
81-4	1400	90	102.7	4.3	8.0
75-4	1600	55	158.8	7.9	11.2
83-6	1600	55	161.4	6.2	8.9
81-6	1800	27	89.0	7.8	16.2
87-4	1800	27	97.1	8.3	16.7
Property Specification Minimums	1400 1800	95 30	23.0 23.0	3.0 4.0	

*2175°F for 2 hours with Argon Quench; plus 1950°F for 2 hours with Argon Quench; plus 1400°F for 16 hours with air cooling.

EL = Elongation
RA = Reduction of Area

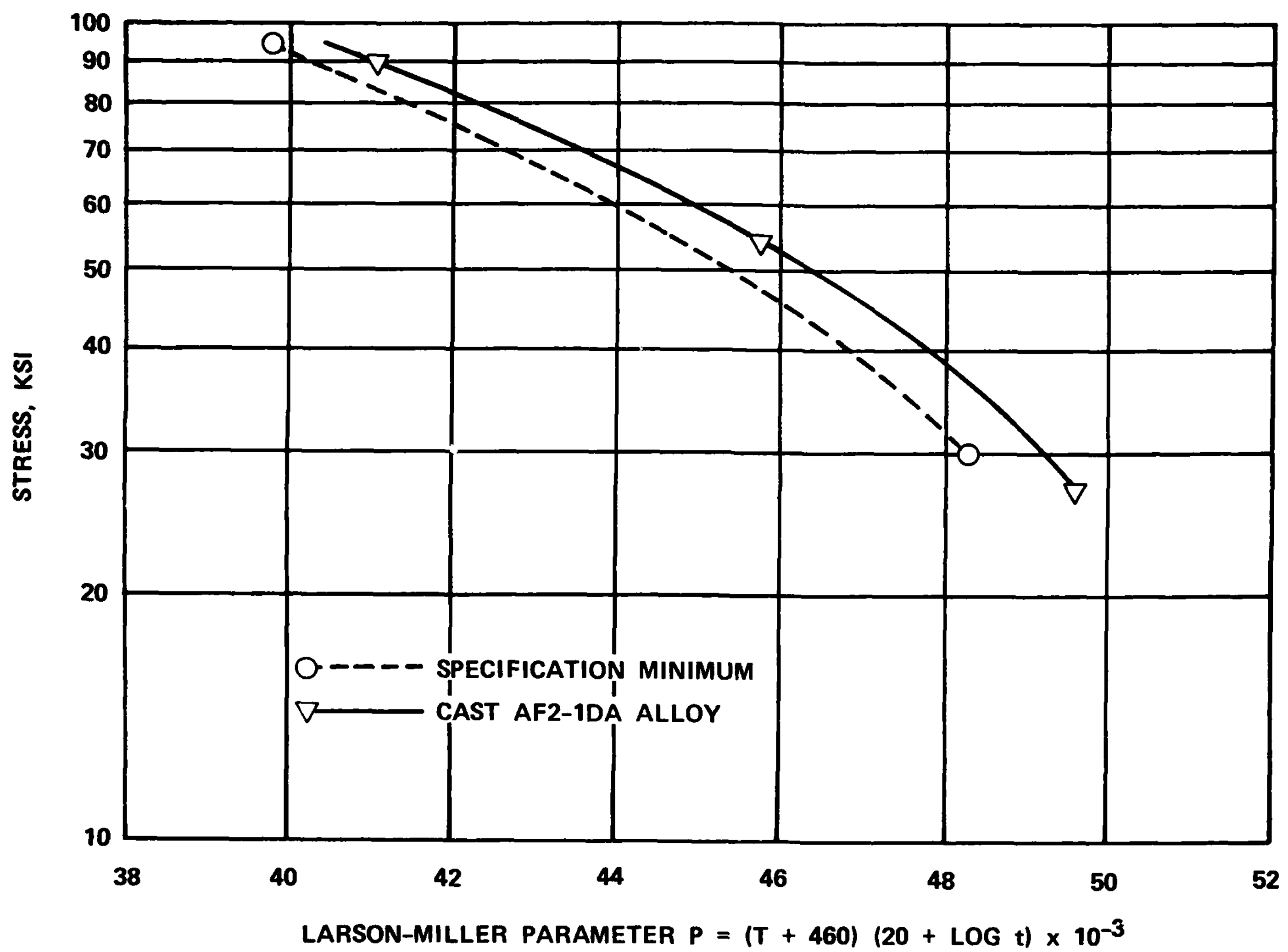


Figure 8. Average stress-rupture test results of heat-treated (un-hipped) cast AF2-1DA alloy turbine wheels compared to specification minimums

Axial strain controlled LCF testing was conducted at room temperature using the specimen configuration shown in Figure 13. This data, as shown in Table 5, was used as the data base with which the HIPped AF2-1DA material was compared (Task II). Baseline LCF properties were measured using an A-ratio of infinity (∞).

SEM examination of the LCF test bar fracture surfaces revealed that origins were associated with primary MC carbides and initiated on the bar external surface. Some microporosity was observed near the origins.

2.2 Task II - Application and Evaluation of HIP and Revised Heat Treatment

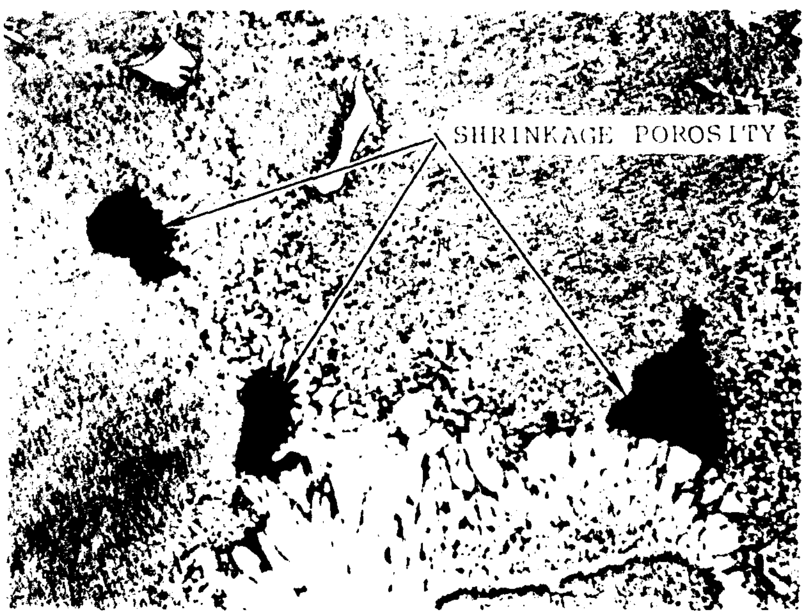
Parameters for HIP of various alloys have been developed by AFWAL/ML (GE refined) and various other companies. A large production cast radial turbine wheel for superalloy INCO 713LC is now being HIPped using AiResearch developed parameters.

2.2.1 HIP and Heat Treatment

Thirty-two cast AF2-1DA turbine wheels were selected and prepared (riser portion of wheel removed) for HIP. Four HIP runs were made using eight turbine wheels per run. Three runs were made at Industrial Materials Technology (IMT), Woburn, Mass., with the parameters shown below. These parameters were selected to cover the range currently in use for cast superalloys.

- o 2200 ±25°F for 3 hours at 15,000 psi, argon
- o 2225 ±25°F for 3 hours at 15,000 psi, argon
- o 2250 ±25°F for 3 hours at 15,000 psi, argon

SAMPLE 72-4



SAMPLE 81-5

Figure 9. Microstructure of as cast AF2-1DA showing typical shrinkage porosity
Mag: 400X Etch: Electrolytic oxalic acid

TABLE 5. ROOM TEMPERATURE LOW-CYCLE FATIGUE (LCF) PROPERTIES OF HEAT-TREATED* (UN-HIPped) CAST AF2-1DA ALLOY TURBINE WHEELS

Specimen Number	Total Strain Range (%)	Measured Modulus (E times 10^6 psi)	Cycles to Failure
72-1	0.77	26.1	3,957
87-2	0.69	29.0	14,894
75-1	0.66	30.9	7,974
75-2	0.65	31.3	17,722
83-1	0.62	32.9	13,182
83-2	0.60	33.3	8,932
81-1	0.60	33.1	10,111
87-1	0.60	33.8	13,221

Test Parameters: Axial Strain Control, A Ratio = ∞
20 CPM Frequency and 200 KSI
Pseudo-Stress

*2175°F for 2 hours with Argon Quench; Plus
1950°F for 2 hours with Argon Quench; Plus
1400°F for 16 hours with air cooling.

The fourth run was made at Battelle Memorial Institute (BMI), Columbus, Ohio, at conditions of 2150 ±25°F for 3 hours at 29,000 psi, argon. These HIPped turbine wheels were heat-treated using the HIP/heat treatment combinations as shown in Table 6.

2.2.2 Mechanical Property Determinations

After heat treatment, the turbine wheels were processed to obtain material for mechanical property (tensile, stress-rupture, and LCF) testing and metallographic examination. Tensile test results performed on 0.250-inch diameter by 1-inch gauge section bars are shown in Tables 7 and 8 for room temperature and 1400°F respectively. Tensile test results showed a trend toward slightly reduced ultimate strength and increased ductility, when compared with the as-cast baseline. Stress-rupture test results performed on 0.250-inch diameter by 1-inch gauge section bars are presented in Tables 9, 10 and 11 for 1400, 1600, and 1800°F respectively. Although most test results exceeded AiResearch specification minimums, the 1400°F stress-rupture properties were poor on material HIPped at 2150°F and solution treated at 2175°F.

The general trends of HIP/heat treat processing parameters on stress-rupture life were:

- Equivalent to higher average rupture life at 1400, 1600 and 1800°F utilizing a higher solution heat treatment with a given HIP condition

- Equivalent to slightly lower average rupture life at 1400, 1600 and 1800°F (with the exception noted above) after HIP/heat treat processing compared to the un-HIPped heat treated baseline

TABLE 6. HIP/HEAT TREATMENT COMBINATIONS	
Combination	No. of Wheels
HIP A + HT1	4
HIP A + HT3	4
HIP B + HT1	4
HIP B + HT3	4
HIP C + HT1	4
HIP C + HT2	4
HIP D + HT1	4
HIP D + HT4	4

HIP Parameters

A = 2150°F/29 KSI/3 hours

B = 2200°F/15 KSI/3 hours

C = 2225°F/15 KSI/3 hours

D = 2250°F/15 KSI/3 hours

Heat Treatment

HT1 = 2175°F (2 hours), plus 1950°F (2 hours), plus 1400°F (16 hours)

HT2 = 2210°F (2 hours), plus 1950°F (2 hours), plus 1400°F (16 hours)

HT3 = 2225°F (2 hours), plus 1950°F (2 hours), plus 1400°F (16 hours)

HT4 = 2250°F (2 hours), plus 1950°F (2 hours), plus 1400°F (16 hours)

TABLE 7. ROOM TEMPERATURE TENSILE PROPERTIES OF HIPped AND HEAT-TREATED* CAST AF2-1DA TURBINE WHEELS

Specimen Number	HIP Parameter (°F/ksi/hrs)	Solution Temp(°F)	0.2% YS (ksi)	UTS (ksi)	EL (%)	RA (%)
51-3	2150/29/3	2175	121.6	135.2	7.3	12.1
77-3			122.0	131.6	6.9	6.9
88-3			125.8	144.9	6.6	10.4
45-3		2225	119.6	128.2	6.3	14.2
64-3			130.0	133.1	3.4	6.4
91-3			124.4	133.0	3.9	11.5
41-3	2200/15/3	2175	127.6	144.3	4.9	9.4
60-3			119.4	138.0	7.2	9.6
95-3			123.3	130.4	4.4	8.9
69-3		2225	119.7	128.3	5.6	8.5
78-3			126.8	142.9	5.9	8.9
82-3			128.0	143.2	5.7	9.9
48-3	2225/15/3	2175	121.4	123.9	3.9	13.7
63-3			124.6	131.7	4.6	15.0
93-3			124.8	135.0	5.3	10.8
68-3		2210	120.6	131.3	6.6	13.5
76-3			119.5	132.2	7.5	9.1
80-3			127.8	139.0	5.6	11.9
66-3	2250/15/3	2175	129.3	130.3	6.1	13.0
86-3			119.0	127.5	6.6	16.9
92-3			127.7	135.8	4.8	12.0
61-3		2250	123.9	139.6	3.9	11.9
67-3			121.3	134.4	8.9	13.0
89-3			117.2	122.8	7.5	17.4
Property Specification Minimum			115.0	130.0	5.0	-

*At indicated solution temperature for 2 hours with Argon quench; plus 1950°F for 2 hours with Argon quench; plus 1400°F for 16 hours with air cooling.

HIP = Hot Isostatic Pressing
YS = Yield Strength
UTS = Ultimate Tensile Strength
EL = Elongation
RA = Reduction Area

TABLE 8. 1400°F TENSILE PROPERTIES OF HIPped AND HEAT-TREATED* CAST AF2-1DA TURBINE WHEELS						
Specimen Number	HIP Parameter (°F/ksi/hrs)	Solution Temp(°F)	0.2% YS (ksi)	UTS (ksi)	EL (%)	RA (%)
51-5	2150/29/3	2175	106.7	133.4	7.0	13.0
77-5			111.4	140.0	7.1	10.5
96-5			114.0	142.0	4.9	11.8
64-5		2225	117.8	128.1	4.9	9.1
73.5			120.3	146.9	5.6	11.1
91.5			114.9	149.4	7.8	8.3
41-5	2200/15/3	2175	109.0	144.5	8.1	10.9
71-5			111.7	130.3	5.6	11.1
95-5			105.9	126.7	5.6	13.8
78-5		2225	118.8	143.6	5.9	10.8
82-5			110.8	149.1	5.7	10.3
90-5			104.8	133.6	8.9	13.7
63-5	2225/15/3	2175	112.6	138.8	6.5	15.5
79-5			108.0	139.1	6.0	10.3
93-5			105.4	140.6	9.0	13.3
76-5		2210	105.9	142.7	7.9	11.5
80-5			109.9	136.0	6.4	13.8
85-5			111.8	137.7	7.3	9.3
70-5	2250/15/3	2175	114.6	146.0	6.9	16.4
86-5			106.1	139.7	7.7	11.6
92-5			105.6	131.2	5.9	11.2
61-5		2250	112.1	145.7	8.9	12.8
74-5			109.7	134.7	6.4	11.8
89-5			107.1	111.9	2.7	5.1
Property Specification Minimum			105.0	130.0	5.0	-

*At indicated solution temperature for 2 hours with Argon quench; plus 1950°F for 2 hours with Argon quench; plus 1400°F for 16 hours with air cooling.

HIP = Hot Isostatic Pressing
YS = Yield Strength
UTS = Ultimate Tensile Strength
EL = Elongation
RA = Reduction Area

TABLE 9. 1400°F CREEP-RUPTURE PROPERTIES OF HIPped AND HEAT-TREATED* CAST AF2-1DA TURBINE WHEELS

Specimen Number	HIP Parameter (°F/ksi/hrs)	Solution Temp(°F)	Temp (°F)	Stress (ksi)	Rupture Time (Hours)	EL (%)	RA (%)
51-4	2150/29/3	2175	1400	95	9.6	3.6	15.9
96-6		2175			20.9	3.4	9.2
45-4		2225			69.1	3.5	10.0
91-6		2225			75.1	4.8	12.7
41-4	2200/15/3	2175			91.5	4.6	12.2
95-6		2175			12.6	4.0	13.8
69-4		2225			76.3	3.6	8.4
82-6		2225			24.3	4.2	13.8
48-4	2225/15/3	2175			44.2	4.2	10.1
93-6		2175			53.5	5.6	9.5
68-4		2210			28.6	3.8	13.0
80-6		2210			133.1	6.3	11.3
66-4	2250/15/3	2175			64.0	5.0	10.1
92-6		2175			23.3	6.1	13.3
61-4		2250			71.9	5.2	6.9
67-4		2250			54.0	5.5	12.3
Specification Minimum					23.0	3.0	-

*At indicated solution temperature for 2 hours with Argon quench; plus 1950°F for 2 hours with Argon quench; plus 1400°F for 16 hours with air cooling.

HIP = Hot Isostatic Pressing
EL = Elongation
RA = Reduction Area

TABLE 10. 1600°F CREEP-RUPTURE PROPERTIES OF HIPped AND HEAT-TREATED* CAST AF2-1DA TURBINE WHEELS

Specimen Number	HIP Parameter (°F/ksi/hrs)	Solution Temperature (°F)	Temperature (°F)	Stress (ksi)	Rupture Time (Hours)	EL (%)	RA (%)
51-6	2150/29/3	2175	1600	60	68.8	12.0	17.9
77-4		2175			53.5	9.9	10.9
64.4		2225			87.3	7.1	8.6
73.6		2225			89.9	8.5	8.9
41.6	2200/15/3	2175			41.5	10.5	24.3
60-4		2175			60.0	10.2	15.1
69-6		2225			58.7	11.2	16.7
90-4		2225			68.5	8.0	9.5
63-4	2225/15/3	2175			50.4	9.9	14.1
79-6		2175			51.8	7.3	18.2
76-4		2210			82.8	6.9	8.9
85-4		2210			84.1	6.0	7.5
70-6	2250/15/3	2175			57.7	8.5	16.6
84-4		2175			39.5	8.8	15.1
67-6		2250			61.3	6.0	11.4
89-4		2250			2.0	1.9	1.9

*At indicated solution temperature for 2 hours with argon quench; plus 1950°F for 2 hours with argon quench; plus 1400°F for 16 hours with air cooling.

HIP = Hot Isostatic Pressing

EL = Elongation

RA = Reduction Area

TABLE 11. 1800°F CREEP-RUPTURE PROPERTIES OF HIPped AND HEAT-TREATED* CAST AF2-1DA TURBINE WHEELS

Specimen Number	Solution HIP Parameter (°F/ksi/hrs)	Temperature (°F)	Temperature (°F)	Stress (ksi)	Rupture Time (Hours)	EL (%)	RA (%)
77-6	2150/29/3	2175	1800	30	46.8	13.9	17.3
88-4		2175			48.7	13.2	28.0
64-6		2225			66.4	7.5	15.3
91-4		2225			40.7	10.1	21.6
71-6	2200/15/3	2175			55.2	9.8	14.3
95-4		2175			37.5	11.8	25.7
78-4		2225			46.8	11.5	24.0
90-6		2225			55.5	13.4	23.7
63-6	2225/15/3	2175			57.1	7.0	8.5
93-4		2175			38.0	9.0	23.3
76-6		2210			40.1	8.8	12.0
85-6		2210			42.3	8.5	17.5
86-6	2250/15/3	2175			38.0	7.2	10.5
92-4		2175			41.1	11.0	20.9
89-6		2250			51.2	11.7	21.9
89-6		2250			37.5	11.1	18.8
Specification Minimum					23.0	4.0	—

*At indicated solution temperature for 2 hours with argon quench; plus 1950°F for 2 hours with argon quench; plus 1400°F for 16 hours with air cooling.

HIP = Hot Isostatic Pressing

EL = Elongation

RA = Reduction Area

2.2.3 Metallographic Study

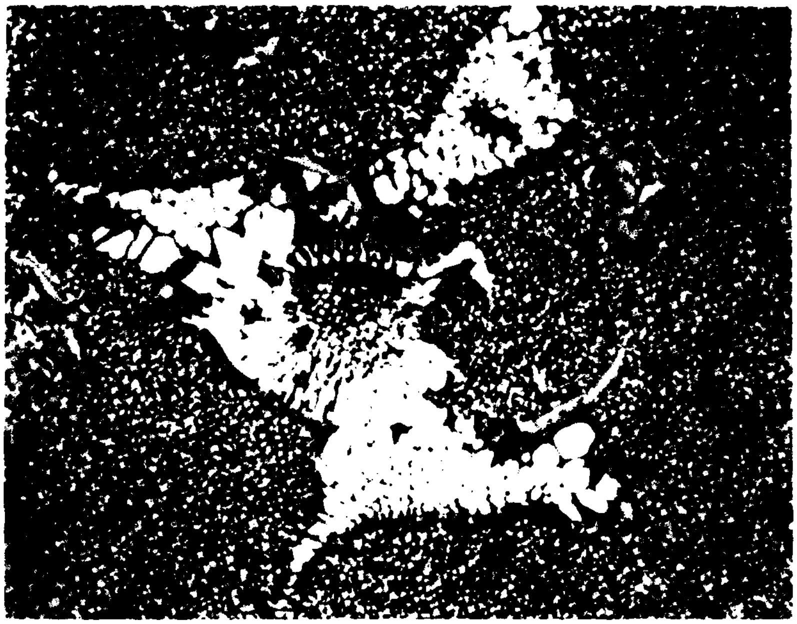
Microstructural studies were performed on each HIP/heat treatment combination and results compared with the as-cast and heat treated baseline material. Figure 9, previously included, shows the as-cast material with typical shrinkage voids in cast AF2-1DA. Material HIPped at 2150 and 2200°F is shown in Figure 10. No evidence of voids was detected indicating closure by HIP. Figure 11 shows material HIPped at 2225 (void free) and 2250°F, (voids due to incipient melting) during HIP. HIP temperatures of 2225, 2200 and 2150°F, resulted in closed porosity, while 2250°F caused voids and partial solutioning of the gamma/gamma prime eutectic phase in the microstructure.

The effects of solution heat treating temperature on void formation due to incipient melting is shown in Figure 12. As can be seen, no voids are evident in the 2175 and 2210°F solution heat treated microstructures. The 2225 and 2250°F solution heat treated microstructures exhibit void formation caused by incipient melting. Effects of solution temperature on cooling gamma prime and gamma/gamma prime eutectic phases after HIP compared with as-cast and heat treated baseline material were:

- o More undissolved cooling gamma prime and no change in eutectic gamma prime at 2175°F for 2 hours

- o 95-percent solutioning of cooling gamma prime and no change in gamma/gamma prime eutectic at 2210°F for 2 hours

- o Complete solutioning of cooling gamma prime and slight solutioning of gamma/gamma prime eutectic at 2225°F for 2 hours

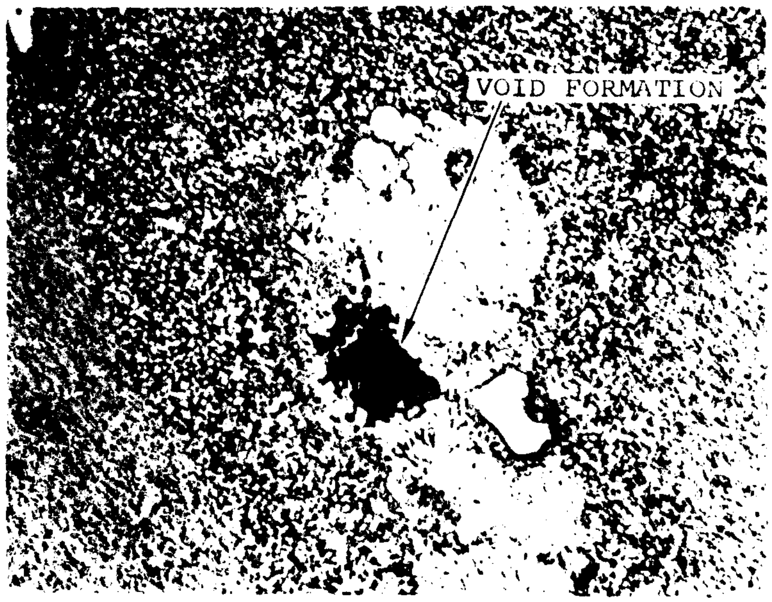


HIP TEMPERATURE: 2150°F

HIP TEMPERATURE: 2200°F

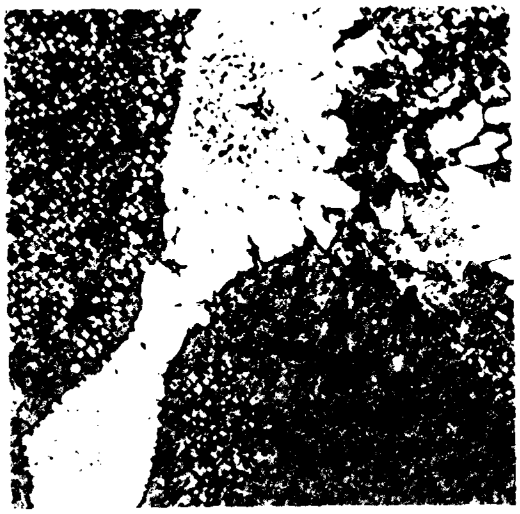
Figure 10. Microstructure of HIPped AF2-1DA alloy
Mag: 4001X Etch: Electrolytic oxalic acid

HIP TEMPERATURE: 2225°F

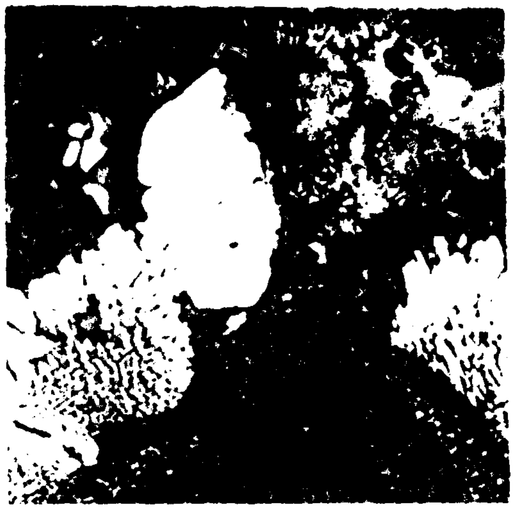


HIP TEMPERATURE: 2250°F

Figure 11. Microstructure of HIPped AF2-1DA alloy note void formation from incipient melting after 2250°F hip
Mag: 400X Etch: Electrolytic oxalic acid



SOLUTION: 2175°F



SOLUTION: 2210°F

SOLUTION: 2225°F

SOLUTION: 2250°F

Figure 12. Microstructure of HIPped AF2-1DA showing effects of solution heat treatment temperature on void formation
Mag: 400X Etch: Electrolytic oxalic acid

- o Complete solutioning of cooling gamma prime and gamma/gamma prime eutectic at 2250°F for 2 hours

2.2.4 LCF Evaluation

Tensile and stress-rupture test results and observed microstructure changes (void closure and subsequent formation during heat treatment), were used to select four of eight HIP/heat treatment combinations for LCF evaluation. Material processed at 2250°F was eliminated from LCF evaluation due to the incipient melting voids. Material HIPped at 2150°F and solution treated at 2175°F showed poor 1400°F stress-rupture properties and was also eliminated. The remaining five HIP/heat treatment combinations were reduced to four by selecting combinations that would help establish usable manufacturing process ranges for HIP and solution heat treatment. The four combinations are shown below:

Combination	HIP	Solution Heat Treatment*
1	2200°F/15 ksi/3 hours	2175°F
2	2200°F/15 ksi/3 hours	2225°F
3	2225°F/15 ksi/3 hours	2175°F
4	2225°F/15 ksi/3 hours	2210°F

*Total heat treatment is solution temperature for 2 hours/rapid argon gas quench plus 1950°F for 2 hours/rapid argon gas quench plus 1400°F for 16 hours/air cool.

Strain control LCF tests were conducted with eight bars (Figure 13) machined from each of the four selected HIP/heat treatment combinations. Test conditions duplicated baseline, as-cast and heat treated material; room temperature, $A = \infty$, 20 cpm and 200 ksi pseudo-stress (product of strain times Youngs Modulus). Test results are presented in Tables 12 and 13.

Improved LCF life data, compared with the cast plus heat treated baseline material is indicated for each HIP/heat treatment combination. Figures 14 through 17 reflect Weibull

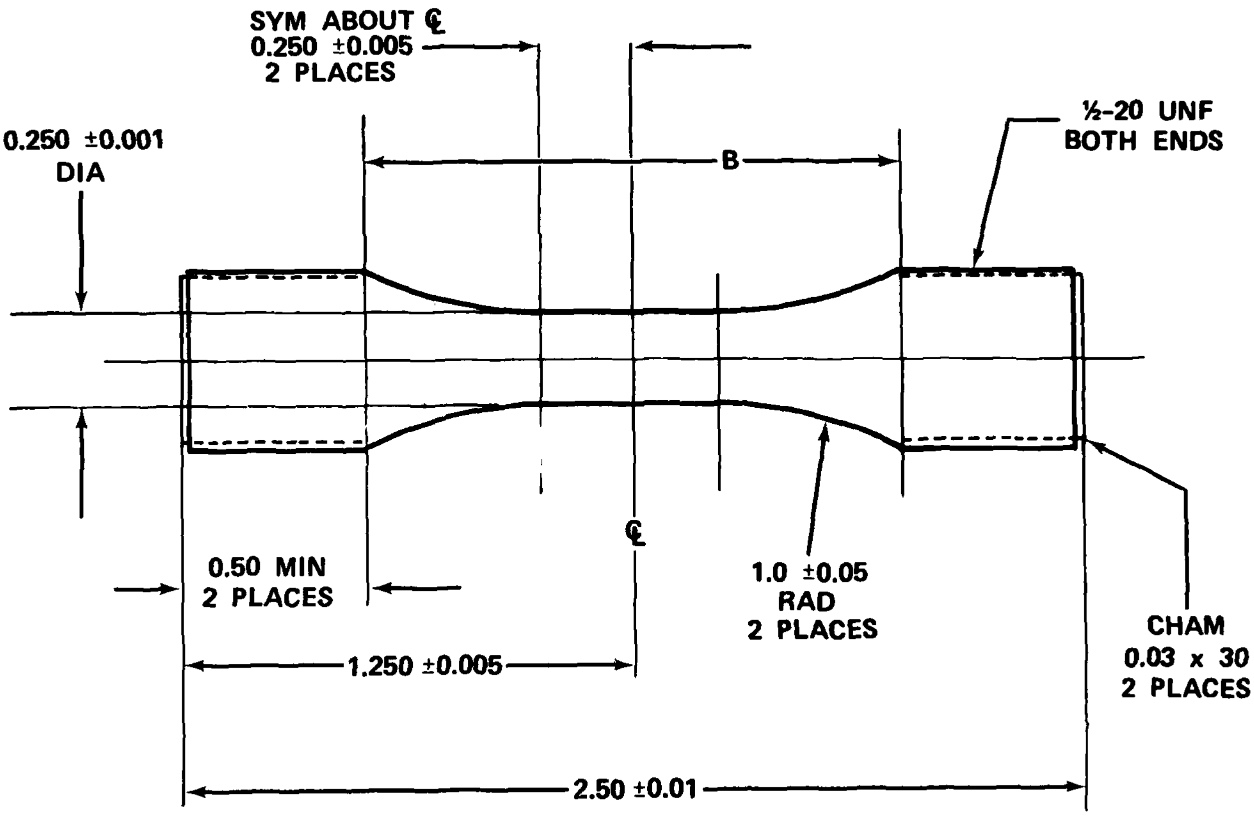


Figure 13. Uniform section LCF test specimen

TABLE 12. ROOM TEMPERATURE LOW-CYCLE-FATIGUE (LCF) PROPERTIES OF HIPped AND HEAT-TREATED* CAST AF2-1DA ALLOY TURBINE WHEELS.

Specimen Number	HIP Parameter (°F/ksi/hrs)	Solution Temperature (°F)	Total Strain Range (%)	Measured Modulus (E times 10^6 psi)	Cycles to Failure	Remarks
71-1	2200/15/3	2175	0.86	23.2	9,080	
71-2			0.79	25.4	9,128	
60-1			0.64	31.1	10,901	
95-1			0.62	32.2	25,566	
41-2			0.60	34.1	15,998	
95-2			0.55	36.2	22,144	
60-2			0.54	36.7	21,011	
41-1			0.52	38.2	23,414	
90-1		2225	0.69	29.5	14,392	
82-2			0.69	32.8	1,892	226 ksi pseudo-stress
82-1			0.66	30.3	11,455	
69-1			0.66	31.0	8,539	
69-2			0.61	32.7	13,180	
78-1			0.59	34.5	16,427	
78-2			0.57	34.9	15,651	
90-2			0.47	42.6	20,603	

Test Parameters: Axial strain control, A Ratio = ∞, 20 Hz frequency and 200 ksi pseudo-stress

*At indicated solution temperature for 2 hours with argon quench; plus 1950°F for 2 hours with argon quench; plus 1400°F for 16 hours with air cooling.

TABLE 13. ROOM TEMPERATURE LOW-CYCLE-FATIGUE PROPERTIES OF HIPped AND HEAT-TREATED* CAST AF2-1DA ALLOY TURBINE WHEELS.

Specimen Number	HIP Parameter (°F/ksi/hrs)	Solution Temperature (°F)	Total Strain Range (%)	Measured Modulus (E times 10^6 psi)	Cycles to Failure	Remarks
79-1	2225/15/3	2175	0.65	31.0	10,840	
63-1			0.63	31.7	13,538	
48-2			0.60	33.5	9,108	
63-2			0.55	34.1	13,781	188 ksi pseudo-stress
93-2			0.54	36.9	22,047	
48-1			0.53	37.5	24,318	
93-1			0.52	38.3	15,970	
79-2			-	-	-	Specimen buckled equipment malfunction
80-2		2210	0.85	23.4	6,168	
80-1			0.76	26.7	8,177	
85-2			0.71	28.1	9,218	
76-1			0.70	28.5	16,146	
85-1			0.67	30.0	16,986	
76-2			0.57	35.0	13,312	
68-2			0.52	38.5	21,560	
68-1			0.47	42.7	7,567	

Test Parameters: Axial strain control, A ratio = ∞, 20 Hz frequency and 200 ksi pseudo-stress

*At indicated solution temperature for 2 hours with argon quench; plus 1950°F for 2 hours with argon quench; plus 1400°F for 16 hours with air cooling.

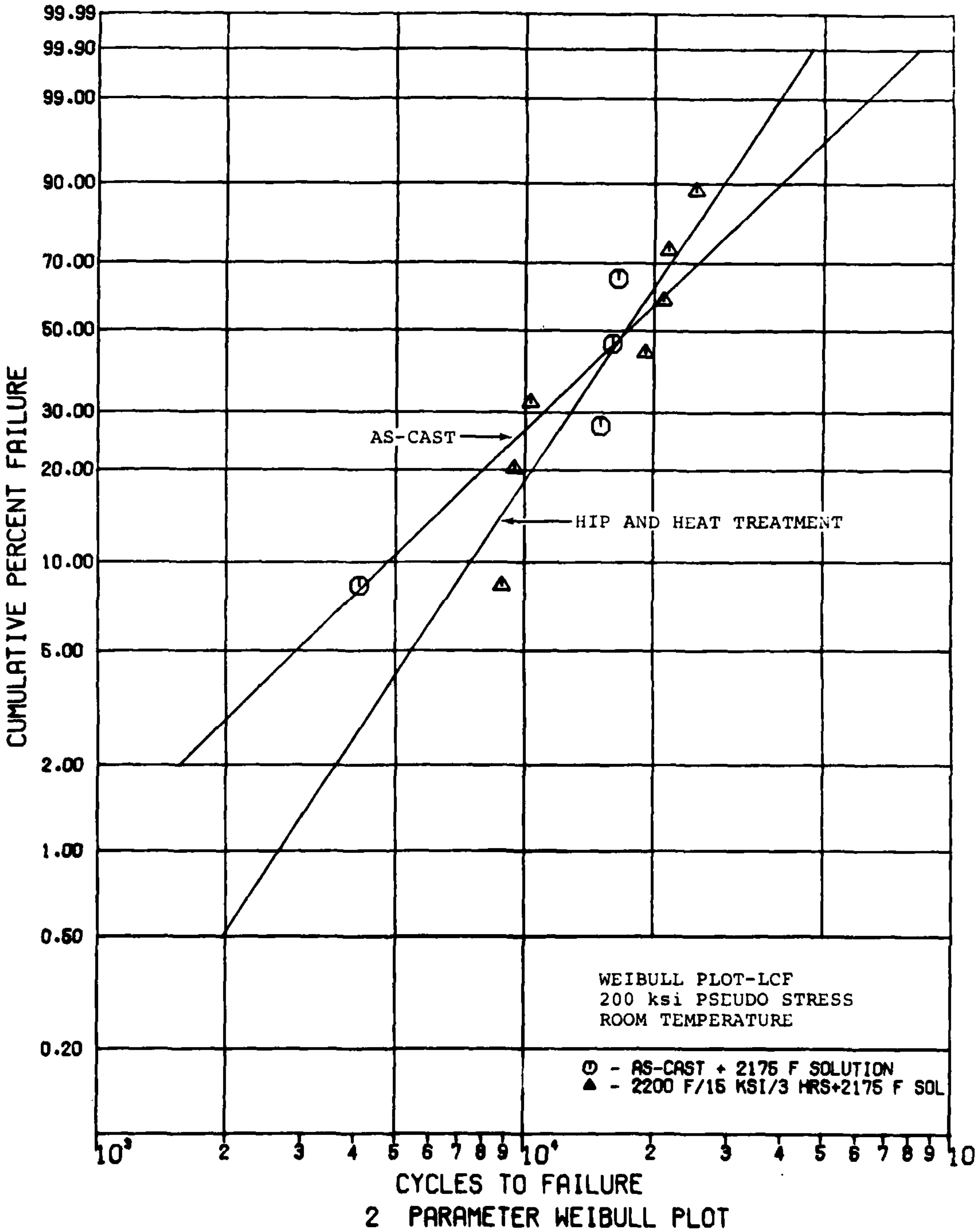


Figure 14. As-cast plus 2175°F solution, 2200°F/15 KSI/3 HRS plus 2175°F solution

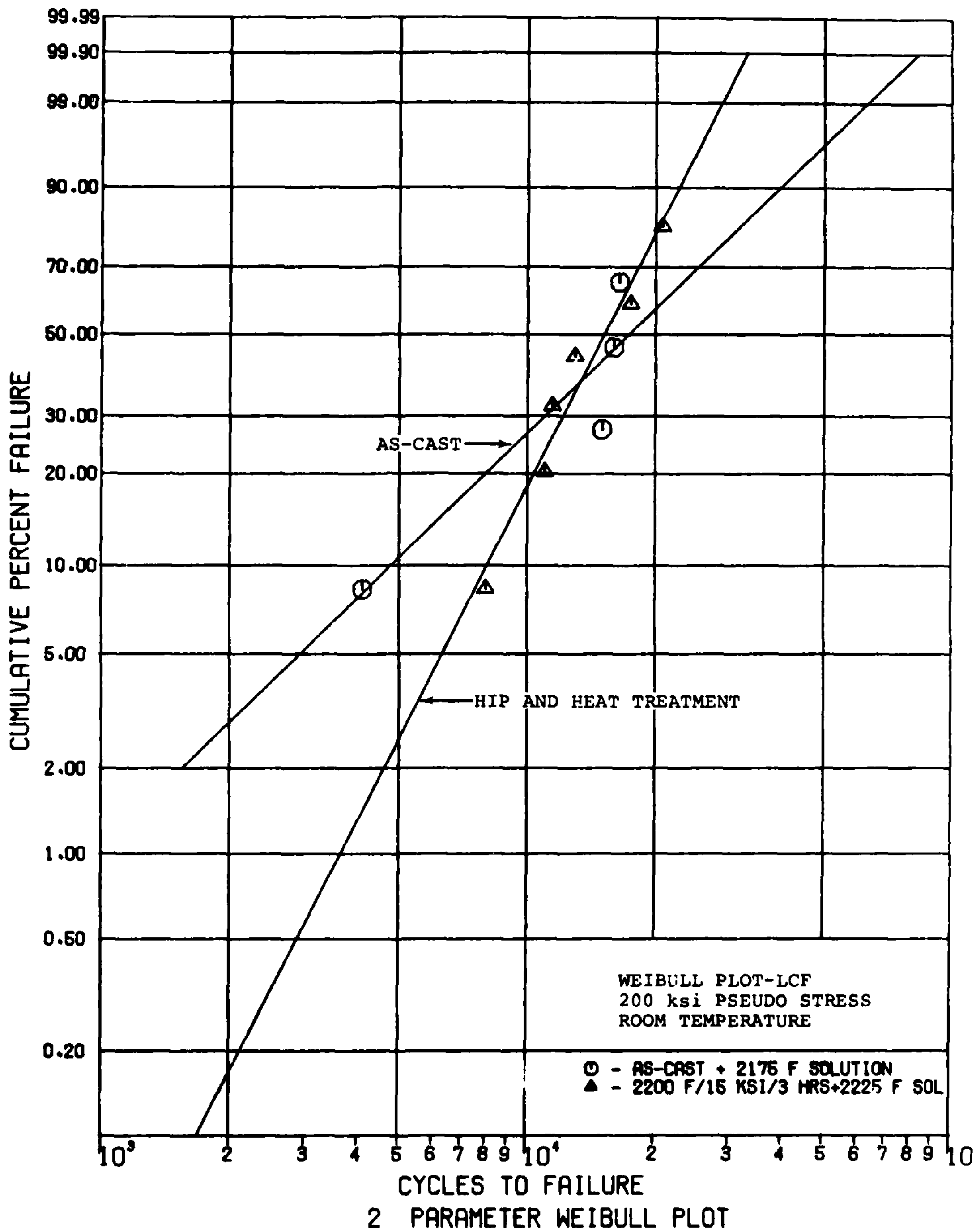


Figure 15. As-cast plus 2175°F solution, 2200°F/15 KSI/3 HRS plus 2225°F solution

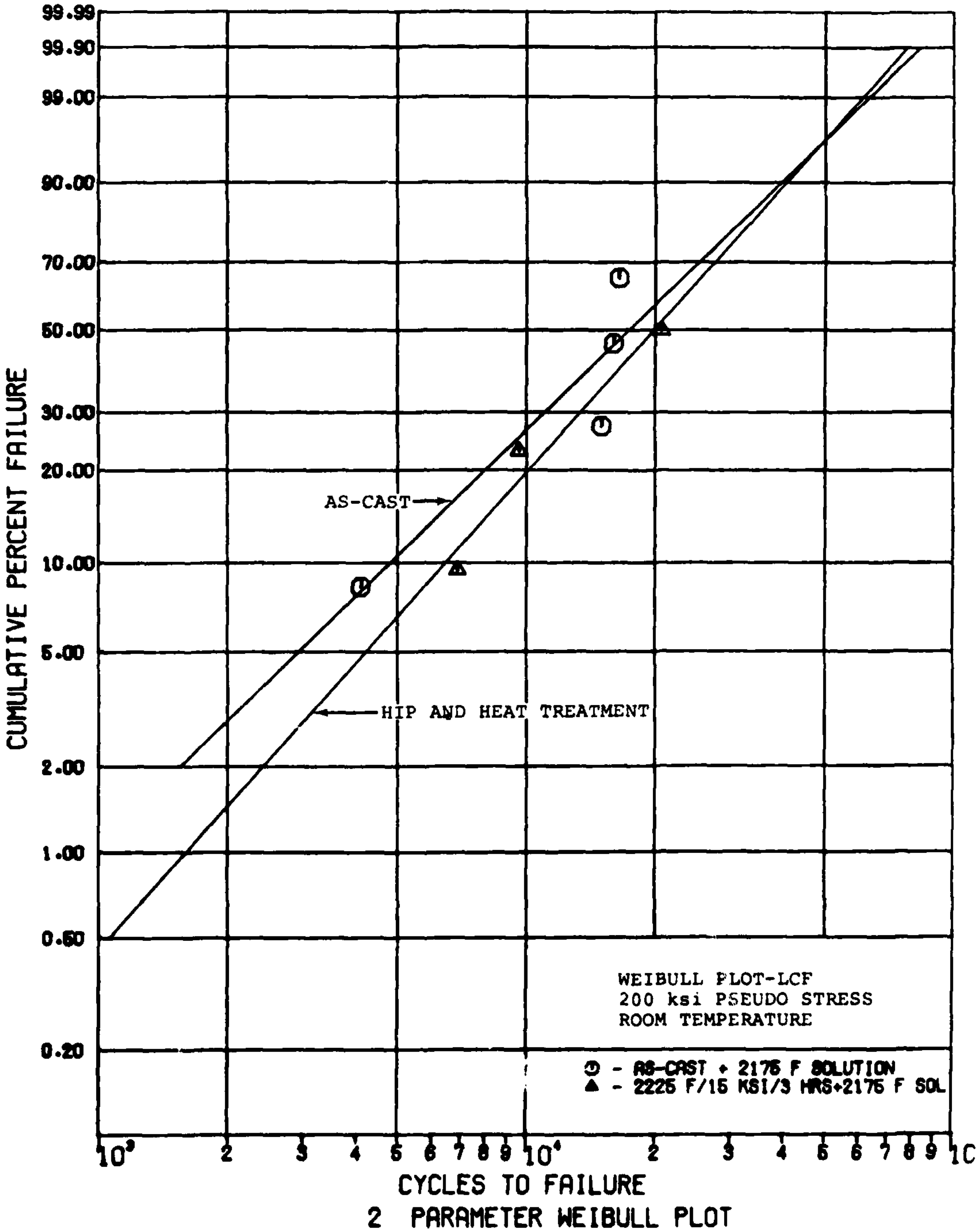


Figure 16. As-cast plus 2175°F solution, 2225°F/15 KSI/3 HRS plus 2175°F solution

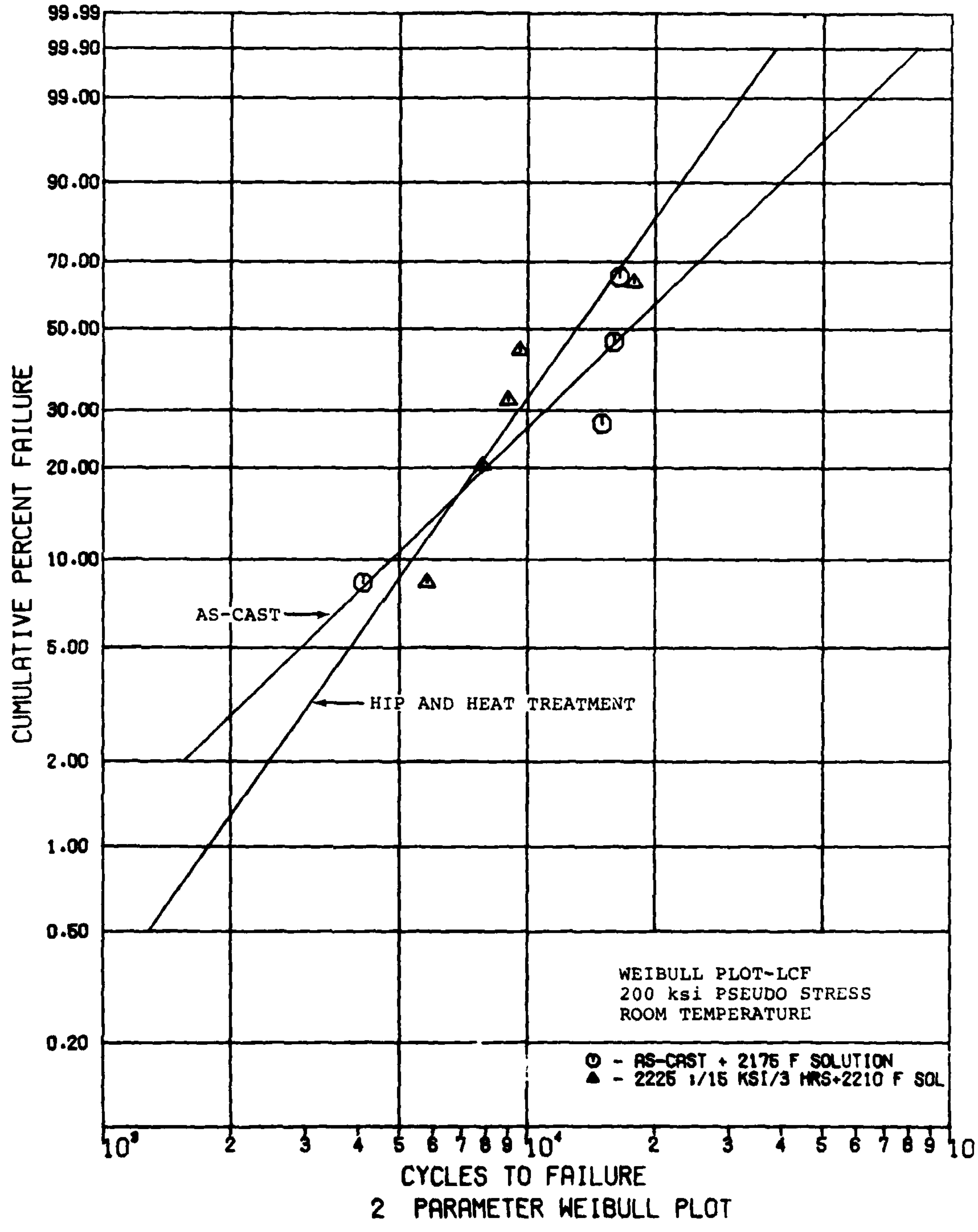


Figure 17. As-cast plus 2175°F solution, 2225°F/15 KSI/3 HRS plus 2210°F solution

plots for individual HIP and heat treatment combinations. Figure 18 shows inclusive HIP data compared with the cast and heat treated baseline. The lower cummulative percent failure range component early failures and is of greatest concern in LCF design considerations. The cumulative HIP curve (Figure 18) shows that at one-percent cumulative failure life, HIP improves life by a factor of three, when compared with the as-cast baseline.

SEM examination of LCF test bar fracture surfaces revealed that origins were again associated with MC carbides and initiated on the external surface. Specimen number 82-2 was the only exception. The fracture surface of this specimen exhibited an internal origin associated with an inclusion type defect as shown in Figure 19. Energy dispersive X-ray analysis revealed that the defect contained areas of high hafnium, tantalum, and titanium. The defect source was not pursued because it was not considered part of this program. Two 2225°F solution heat-treatment specimens, exhibited small voids caused by incipient melting.

2.2.5 Process Selection

Tensile, stress-rupture, and LCF testing of various HIP and heat treatment combinations that resulted in increased fatigue life, were used to define the manufacturing process parameters. Acceptable HIP parameter limits identified were 2200 to 2225°F for 3 hours at 15 ksi argon. However, this range must be extended since HIP vendors typically require a ±25°F nominal temperature variance. The requirement to open the range on the lower end to 2175°F, exists because HIP at 2250°F produced voids. It is assumed the 2175°F/15 ksi parameters will effect closure since the HIP cycle at 2150°F for 3 hours at 29 ksi argon resulted in complete closure. Pressure is well above the 2200°F yield strength of 2,800 to 3,600 psi (see Table 1 previously included).

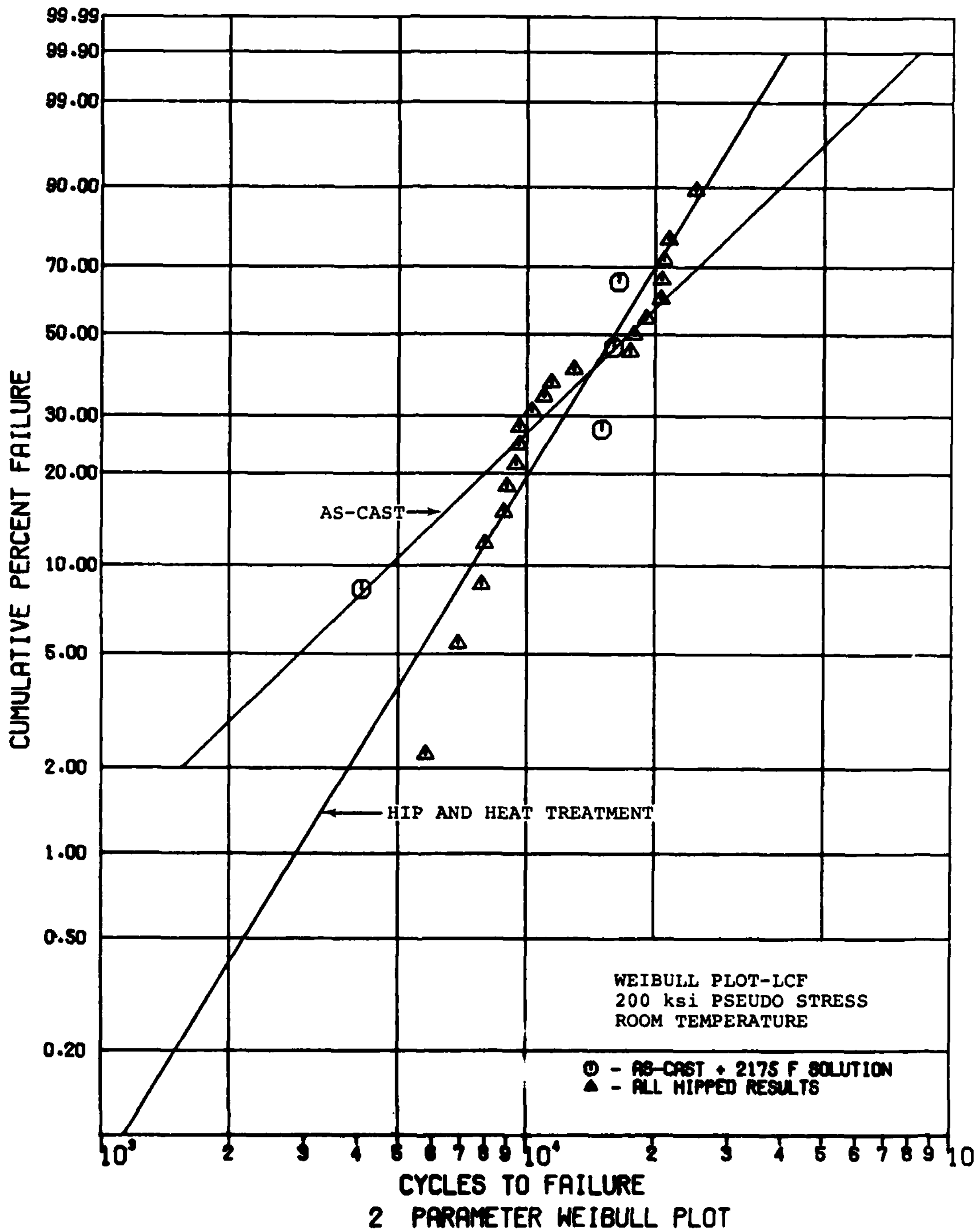


Figure 18. As-cast plus 2175°F solution, all HIPped results.

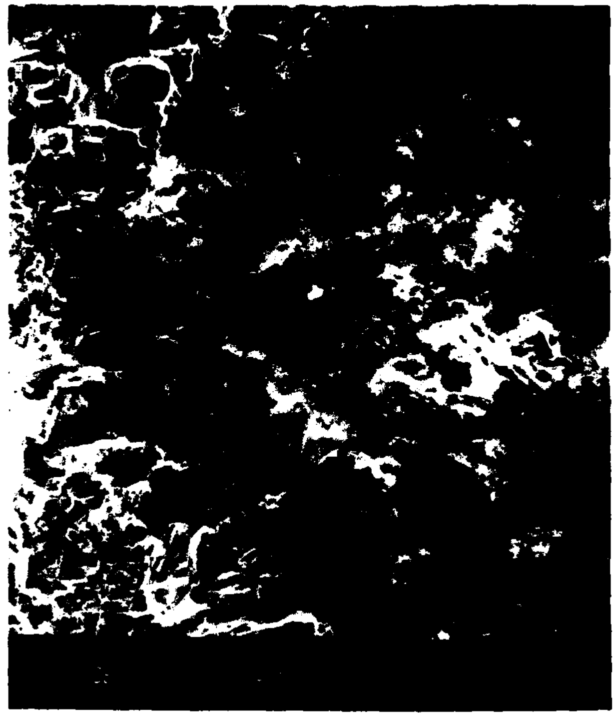


Figure 19. SEM micrographs showing specimen numbered 82-2 LCF test bar fracture surface, exhibiting inclusion type defect (enclosed area). (A) area of high HF, (B) area of high Hf, Ta and Ti and (C) area of fracture origin. This was the only inclusion found on LCF test bar fracture surfaces

Acceptable solution heat treatment temperature range limits, (after HIP) selected from the mechanical property results, are 2175 to 2210°F (2225°F produced voids). These limits need not be extended since this temperature control spread is sufficient for most vacuum furnace operations. Adherence to this critical temperature range is paramount to proper heat treatment.

Recommended HIP/heat treatment manufacturing process parameters are listed below:

- o HIP — 2200 ±25°F/3 hours/15 ksi argon
- o Heat treatment
  - Solution — 2190 $^{+20}_{-15}$°F (2 hours) argon gas quench 40 to 50°F per minute
- o Intermediate Age — 1950 ±25°F (2 hours) argon gas quench 40 to 50°F per minute
  - Age — 1400 ±25°F (16 hours) air cool

Tensile and stress-rupture test results from HIP/heat treatment combinations within acceptable processing ranges, were selected from a large data population and averages analyzed. Table 14 shows room temperature and 1400°F tensile test results compared with as-cast and heat treated baseline and AiResearch specification minimum values. HIP material properties exceed minimum values, exhibit improved ductility, and are comparable with as-cast baseline material.

Stress-rupture results shown in Figure 20 compare as-cast, heat treated, HIP and specification minimum limits on a Larson-Miller plot. Rupture properties after HIP are above minimum values, and comparable to as-cast.

TABLE 14. TENSILE TEST RESULTS OF HIP/HEAT TREATMENT COMBINATIONS* WITHIN ACCEPTABLE PROCESSING RANGES (ALL VALUES ARE AVERAGE)

Room Temperature	0.2% YS (ksi)	UTS (ksi)	EL (%)	RA (%)
Cast + Heat Treated	123.4	134.7	4.2	10.7
HIP + Heat Treated	123.2	134.0	5.6	11.3
Specification Minimum	115.0	130.0	5.0	--
1400°F				
Cast + Heat Treated	112.6	137.1	6.0	14.9
HIP + Heat Treated	109.0	137.4	6.9	12.2
Specification Minimum	105.0	130.0	5.0	--

*Hip/Solution Temperature

2200°F/2175°F

2225°F/2175°F

2225°F/2210°F

HIP = Hot Isotatic Pressing

YS = Yield Strength

UTS = Ultimate Tensile Strength

RA = Reduction of Area

EL = Elongation

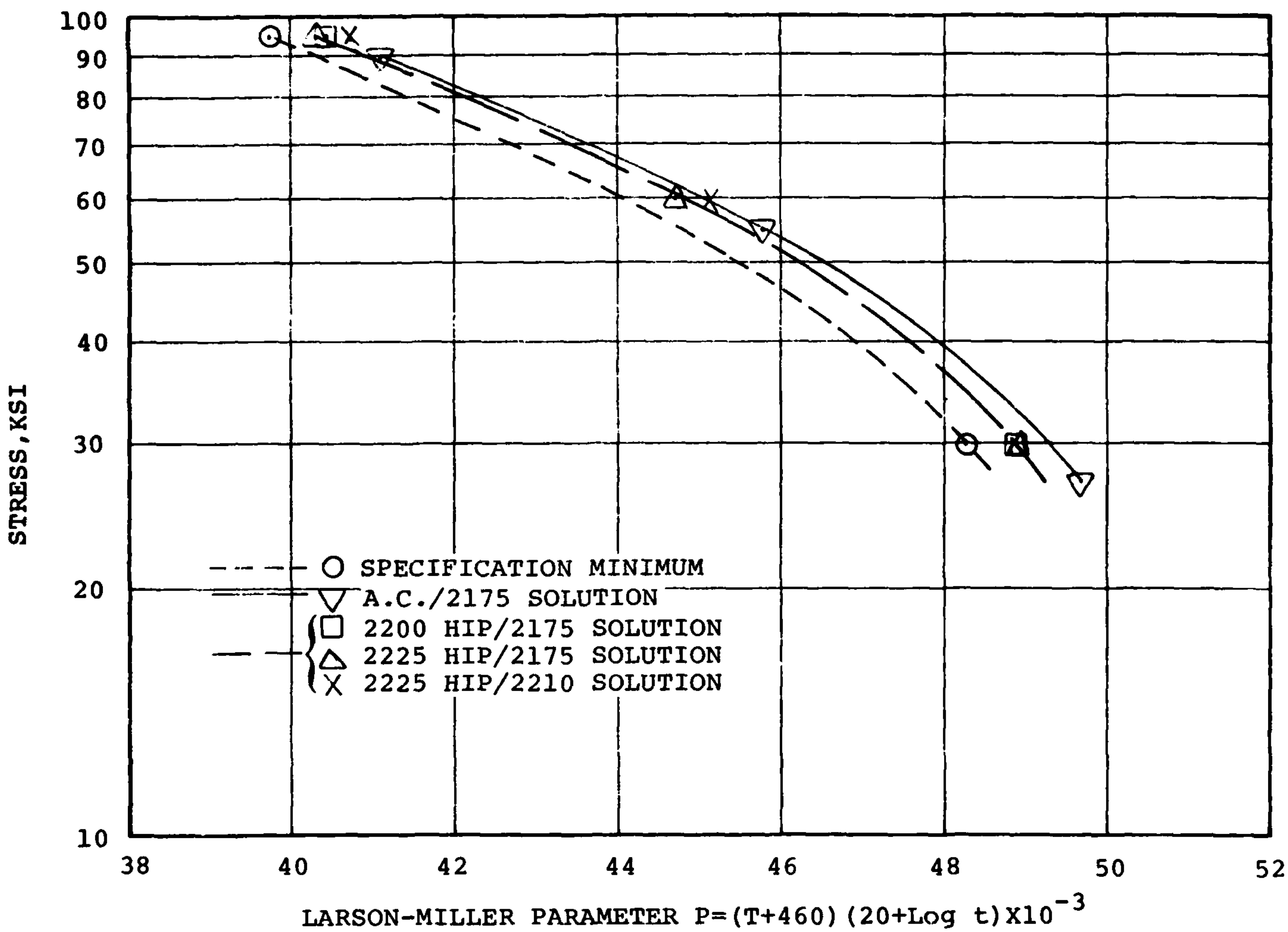


Figure 20. As-cast and HIP stress-rupture test results AF2-1DA alloy compared with AiResearch specifications

SECTION III

CONCLUSIONS AND RECOMMENDATIONS

3.1 Conclusions

- Uniaxial LCF testing indicates life improvement by a factor of 3, for cast AF2-1DA alloy (Mod 2A) turbine wheels, using HIP.

- Tensile and stress-rupture properties of HIPped castings exceed AiResearch specification minimum for cast AF2-1DA alloy and are equivalent to as-cast properties.

3.2 Recommendation

- Cast AF2-1DA alloy (Mod 2A) turbine wheels should be HIPped prior to heat treatment to improve LCF properties.

*U.S.Government Printing Office: 1980 — 657-084/155